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Binaries among Extreme Horizontal Branch Stars in Globular Clusters

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Abstract. Following a review of our present knowledge about blue subdwarf stars in globular clusters, we present an overview of the results of searches for close binaries among these stars, including results previously published in the literature and reporting recent and preliminary results of new data. Previous investigations revealed a lack of close systems in NGC 6752, which we confirm with new, more extensive observations. Our estimate of the close binary fraction in this cluster is only 4%. From a review of the relevant literature, there are indications that a low close binary fraction among extreme horizontal branch (EHB) stars is a common feature in globular star clusters. On the other hand, the field EHB population shows evidence of a remarkably high binary fraction. Such a difference among globular cluster and field populations, although not yet explained in detail on the basis of theoretical models, must necessarily be related to different formation histories for EHB stars in the field and in clusters. In this framework, preliminary results indicate that close systems could be relatively common in the peculiar globular cluster NGC 2808, although the sample of studied stars is still small. This would imply that not all clusters share the same behavior, as far as EHB star formation is concerned. We briefly explore possible explanations for these results.

1. sdB Stars in Globular Clusters

The horizontal branch (HB) is a well-known feature in the color-magnitude diagram (CMD) of Galactic globular clusters (GCs), first discovered by ten Bruggencate (1927) and later identified as a population of stars which, after the evolution

along the red giant branch (RGB), eventually ignite He-burning in the core (Hoyle & Schwarzschild 1955). Greenstein (1971) and Caloi (1972) identified the hotter ($T_{\text{eff}} \geq 20,000$ K) HB extension with the already known field B-type subdwarf (sdB) stars, which as a consequence are also referred to as extreme horizontal branch (EHB) stars.

Because of their intrinsic faintness at optical wavelengths, sdBs in GCs were hardly observed at first (Cox & Salpeter 1961), and only later did it become evident that they were present in many GCs, even at high metallicities (e.g. Rich et al. 1997). Thus they became the most prominent evidence of the well-known *second parameter problem*, i.e. the large degree of variation in HB morphology partly explained by metallicity (the “first parameter”; Sandage & Wallerstein 1960) but not completely accounted for by it (Sandage & Wildey 1967; van den Bergh 1967). Rood (1973) pointed out that the spread in temperature along the HB implies a corresponding spread in envelope mass, bluer stars being less massive, and EHB stars must have lost almost their entire envelope during their evolution. The retained envelope is so thin (about $0.02 M_{\odot}$) that it is insufficient to sustain later evolution along the asymptotic giant branch (AGB), and after He exhaustion in the core EHB stars are predicted to evolve directly to the white dwarf cooling sequence (see Catelan 2007b, for a recent review of low-mass stellar evolution). Investigations have accordingly mainly been focused on finding the mechanism(s) responsible for the heavy RGB mass loss required for EHB formation.

1.1. Models for EHB Star Formation

Many canonical and non-canonical models have been proposed over the past several decades, either considering EHB stars as distinct populations or just as the hotter components of a continuous HB. Some very recent results allow us to focus our attention on some of these scenarios (see also Catelan 2007a, for a discussion in the context of the ultraviolet upturn phenomenon in galaxies).

The recent discovery of a planet orbiting a field sdB star (Silvotti et al. 2007) adds new emphasis on the hypothesis that a sub-stellar body interacting with the expanding envelope of an RGB star can cause heavy mass loss, thus leading to the formation of an sdB star (Soker 1998). Searches for planets around main sequence (MS) stars in GCs have been fruitless thus far (Gilliland et al. 2000; Weldrake et al. 2007); indeed, Soker & Hershenhorn (2007) argue that similar such searches are hopeless, because of the long predicted orbital periods.

A super-solar He abundance in the stellar envelope can enhance the mass loss along the RGB by increasing the RGB tip luminosity, thus leading to the formation of an sdB star. Non-canonical phenomena were invoked including He mixing driven by internal rotation (Sweigart & Mengel 1979; Sweigart 1997) and dredge-up induced by H-shell instabilities (von Rudloff et al. 1988), but the recent discovery of He-enriched sub-populations in ω Cen = NGC 5139 (Bedin et al. 2004; Piotto et al. 2005) and probably NGC 2808 (as suggested by Piotto et al. 2007; D’Antona et al. 2005) suggests that the He enhancement could be primordial. Such He enhancement would also affect the HB morphology (e.g., Lee et al. 2005; D’Antona et al. 2005). Unfortunately, a He enhancement would have little consequence on the stellar surface parameters in this high-temperature regime, independently of its origin, and observed He abundances

are altered by atmospheric phenomena like gravitational settling. Therefore, spectroscopic measurements cannot help decide between the EHB progeny of He-enriched or He-normal stars (e.g., Moehler et al. 2000; Moni Bidin et al. 2007). Note that there do exist even hotter stars along the extension of the HB, the so-called “blue hook stars” (e.g., D’Cruz et al. 2000), which will be discussed below. To the best of our knowledge, the crucial phenomenon suspected to be responsible for their formation has yet to be properly incorporated into the CMD simulations that are usually carried out in the framework of the increased He scenario.

In the dense environment of GCs strong dynamical interactions are expected, and these have often been proposed as the cause of sdB formation through stellar collisions, merging, or encounters involving binary stars, which as a consequence can harden (Heggie 1975) and eventually merge (Bailyn et al. 1992). In support of this hypothesis, Fusi Pecci et al. (1993) and Buonanno et al. (1997) showed that more concentrated or denser clusters tend to have bluer HB types and longer blue HB “tails”, while Djorgovski & Piotto (1992) observed a relation between the dynamical history of GCs and their UV flux, a signature of a hot population that could include sdBs. In some clusters color gradients, with bluer centers, have been identified but, mainly due to low number statistics because the light is dominated by very few bright giants, it is not clear if this feature is a general property of GCs with HB blue tails (Piotto et al. 1988; Djorgovski et al. 2001).

Nevertheless, other observational constraints put this picture in doubt. In fact, one would expect to find EHB stars more concentrated toward cluster centers where interactions are stronger, but no radial gradient has been found in GCs with the most strongly populated EHBs, such as NGC 2808 (Bedin et al. 2000), ω Cen (D’Cruz et al. 2000), NGC 6388 and NGC 6441 (Rich et al. 1997). On the other hand, it should be noted that blue stragglers, which are also supposed to be formed through stellar encounters, are indeed more concentrated in the central regions of all GCs (Piotto et al. 2004). Moreover, the presence of pairs of clusters that are dynamically similar and yet have very different HB morphology (e.g., M 3/M 13 Ferraro et al. 1997), or similar in HB morphology but dynamically very different (e.g., M 15/NGC 288 Crocker et al. 1988) also argue against dynamical interactions as an important channel for EHB star formation.

1.2. Results on EHB stars

As previously noted, there is a large difference between the apparent magnitudes of field sdB stars and their GC counterparts. The nearest sdBs in the Galactic field reach a visual magnitude $V = 10 - 11$, whereas in GCs they are much farther away, and are never brighter than about $V = 17$. To date, the study of EHB stars in GCs has been limited to their photometric properties or low-resolution spectroscopy in few GCs, and many results achieved on field sdBs have not been feasible on EHB cluster stars yet. The most frequent targets of investigations are the nearby GC NGC 6752, and the very massive and peculiar (due to their multimodal HB morphologies and multiple MS) GCs ω Cen and NGC 2808. As a matter of fact, ω Cen is not a typical GC at all, and it has been repeatedly proposed as the nucleus of a merged dwarf galaxy

(Altmann, Catelan, & Zoccali 2005, and references therein), resembling in this sense the case of M 54 (NGC 6715) in the Sagittarius dwarf spheroidal galaxy (Layden & Sarajedini 2000, and references therein).

One important feature in the CMD of many GCs is the often underpopulated region separating sdBs from cooler HB stars. Ferraro et al. (1998) indicated the presence of a gap at about $T_{\text{eff}} = 18,000$ K, while Piotto et al. (1999) argued for a gap at constant stellar mass, with T_{eff} varying with the metallicity of the cluster (see Momany et al. 2004, for a more recent discussion). The presence of this gap suggested to many authors that sdB stars could be a distinct population with a different formation history compared to the other HB stars.

Momany et al. (2002) discovered that EHB stars hotter than $T_{\text{eff}} \approx 23,000$ K deviate from canonical tracks in the CMD of NGC 6752, appearing brighter than expected in U . They argue that this feature could be due to the onset of radiative levitation after the disappearance of the He II convective layer, and this so-called “Momany jump” was later identified also in other clusters (Momany et al. 2004). Unfortunately, no high-resolution spectroscopic analysis has probed this phenomenon so far, and in general there is still a lack of atmospheric abundance measurements for EHB stars in GCs. Support for their hypothesis comes from low-resolution observations by Moehler et al. (2000), who measured a very low He abundance for some targets hotter than 23,000 K ($\log [\text{He}/\text{H}] \leq -3$), and a slight depletion for cooler EHB stars. On the contrary, Moni Bidin et al. (2007) failed to reproduce these results, finding an almost constant He underabundance regardless of temperature ($\log [\text{He}/\text{H}] \approx -2$). On the other hand, among stars hotter than the Momany jump they find puzzling evidence of two distinct groups of stars, with different photometric and spectroscopic properties: the brighter stars are well reproduced by canonical theoretical models, while the remainder show unphysically high masses, which these authors attribute to a mismatch between models and real stars.

Two classes of rapidly pulsating stars are known among field sdB stars (Kilkenny et al. 1997; Green et al. 2003), and they are currently the subject of extensive studies. Asteroseismological techniques are successfully used to analyze their oscillations and derive their physical parameters (Randall et al. 2005). The detection of such pulsators in GCs is a technically challenging issue, which however holds the promise to unveil the physical mechanism(s) that lead to the production of the EHB (and blue hook) stars. Surveys have proven fruitless until now (Reed et al. 2006), but the search is not hopeless and new projects have recently been undertaken (Catelan et al. 2007).

1.3. Blue Hook Stars

Over the past few years, the discovery of very faint EHB stars in the UV CMDs of ω Cen (Whitney et al. 1998) and NGC 2808 (Brown et al. 2001) has drawn considerable attention. These very hot stars form a so-called “blue hook” at the blue end of the HB, and are hotter than the canonical theoretical limit for EHB stars. They were proposed as the progeny of stars which – due to extreme mass loss – did not ignite He at the tip of the RGB, but only later along the WD cooling sequence (“late hot flashers”, e.g., Castellani & Castellani 1993; D’Cruz et al. 1996; Brown et al. 2001). Spectroscopically measured temperatures and He abundances are consistent with the outlined picture (Moehler et al.

2002, 2004). Detailed calculations showed that EHB stars formed through a late He flash should show higher He and C abundances (Cassisi et al. 2003; Lanz et al. 2004) as a consequence of mixing events during the flash, at variance with the primordial He enhancement scenario for which no C overabundance is expected and He should not exceed the primordial (although enhanced) value. Detailed spectroscopic observations should therefore be able to tell between the competing hypotheses. Very recent results by Moehler et al. (2007) strongly support the late-flash scenario. Blue hook stars have also been found in NGC 6388 and NGC 6441 (Busso et al. 2007), NGC 2419 (Ripepi et al. 2007), and M 54 (Rosenberg et al. 2004; Momany et al. 2004; Siegel et al. 2007), and a star spectroscopically studied in M 15 (Moehler et al. 1995) is now recognized as a possible blue hook candidate on the basis of its temperature and He abundance; however, blue hooks are completely lacking in many other clusters. In NGC 6752, for example, the EHB ends at temperatures adequately predicted by standard models, and no blue hook extension is observed. If these stars are the progeny of late flashers, it is unclear why they occur only in the most massive GCs (the clusters named above are among the most massive in the Galaxy; see also Recio-Blanco et al. 2006, for recent evidence pointing to cluster mass as a strong second-parameter candidate).

1.4. Binary sdB Stars

Binary interactions are supposed to play a major role in the formation of sdB stars, as first proposed by Mengel et al. (1976). The most recent models of binary evolution provide a satisfactory explanation for both the origin and observed properties of these stars (Han et al. 2002, 2003). Models in which sdBs arise from binary interaction have also been used to successfully model the observed UV upturn in external galaxies (Han et al. 2007), which is characterized by an increase in UV flux beyond the predictions of canonical population synthesis models, and which is likely to originate from a sdB star population (see for example Greggio & Renzini 1990, and Catelan 2007a for a recent review).

On the observational side, numerous surveys have pointed to the presence of a large population of binaries among field sdB stars, although the results often disagree on the exact binary fraction, probably because of selection effects that affect the samples to different extents. Early investigations focused on the IR flux excess arising from a MS companion unseen at optical wavelengths, and estimated that 50-66% of field sdBs reside in sdB+MS systems (Ferguson et al. 1984; Allard et al. 1994; Ulla & Thejll 1998; Aznar Cuadrado & Jeffery 2001). These surveys brought no information about binary periods, were blind to compact companions, and limited to a lower limit in MS companion mass for the detection. More recently Reed & Stiening (2004) found a much lower fraction for sdB+MS systems (20%), and they argued that previous results were strongly affected by biased samples. Later studies relied on radial velocity (RV) measurements for binary detection. They are more sensitive to short-period systems and higher-mass companions, but searches for wide binaries are ongoing (Morales-Rueda et al. 2006). Maxted et al. (2001) found many RV variables among their sdB targets, mainly with unseen white dwarf companions (sdB+WD binaries), and estimated that nearly 70% of sdBs are close systems. Napiwotzki et al. (2004) found a much lower but still fairly high fraction (about

40%), and many investigations of orbital parameters pointed out that close binaries with period $P \leq 10$ d are very common among field sdB stars (Moran et al. 1999; Saffer et al. 1998; Heber et al. 2002; Morales-Rueda et al. 2004): in fact, such systems are suspected to constitute nearly half of the total Galactic sdB population.

The success of theoretical models and the results of observational investigations have led to the generally accepted conclusion that sdB stars are strictly related to binary interactions, with close systems playing a major role amongst them. It is only over the past few years that similar investigations have started being carried out in globular star clusters as well. These have led to some dramatic, and indeed quite unexpected, results.

2. sdB Binaries in GCs: previous Results

The first results of a search for close binaries among EHB stars in GCs were presented in the second meeting of this series (Moni Bidin et al. 2006a). The analysis of NGC 6752 observations revealed a striking lack of close binary systems: indeed, no close binary was then detected in a sample of 18 targets with $T_{\text{eff}} \geq 20,000$ K. As surveys usually span a large range of temperatures along the HB, this temperature limit will be implicitly assumed to define EHB stars hereafter. The survey was optimized to detect close systems with period $P \leq 10$ d, and it was almost blind to longer periods and/or sdBs with low-mass companions (typically about $0.1 M_{\odot}$, as in the case of the well-known HW Vir system; Menzies & Marang 1986). From these results Moni Bidin et al. (2006c) calculated that, at the 95% confidence level, the close binary fraction among EHB stars in NGC 6752 is lower than 20%. In the same cluster Peterson et al. (2002) had claimed the detection of many radial velocity (RV) variables; however, the reasons for this discrepancy remain unclear (see Moni Bidin et al. 2006c, for a discussion).

Later Moni Bidin et al. (2006b) presented preliminary results of a similar work on two new clusters, namely M 80 (NGC 6093) and NGC 5986. Unfortunately they are far from being as conclusive as the previous ones. In the case of M 80, they detected one good binary candidate out of 11 targets, and derived a most probable close binary fraction $f_{P \leq 10 \text{ d}} = 11\%$, but with large uncertainties because bad weather limited the extent of the observations and accordingly lowered the sensitivity of the survey. On the other hand, in the case of NGC 5986 the temporal coverage was good, leading to the detection of only one (doubtful) candidate; however, the limited sample size (5 targets) prevented a full statistical analysis of the results from being carried out.

It is worth noting that Moni Bidin et al. (2007) individuated in NGC 6752 an EHB star that behaves as an sdB+MS binary (star #5865), being redder than other targets at the same temperature and showing a strong Mg Ib triplet, which is most unusual for these stars.

The picture resulting from these investigations points towards a noticeable lack of close binaries among EHB stars in GCs compared with field sdBs. Many questions have arisen from these results that still await answers based on suitable observational material. In particular, a more precise estimate of f in NGC 6752 is needed in order to better determine how significant the lack of binaries in this

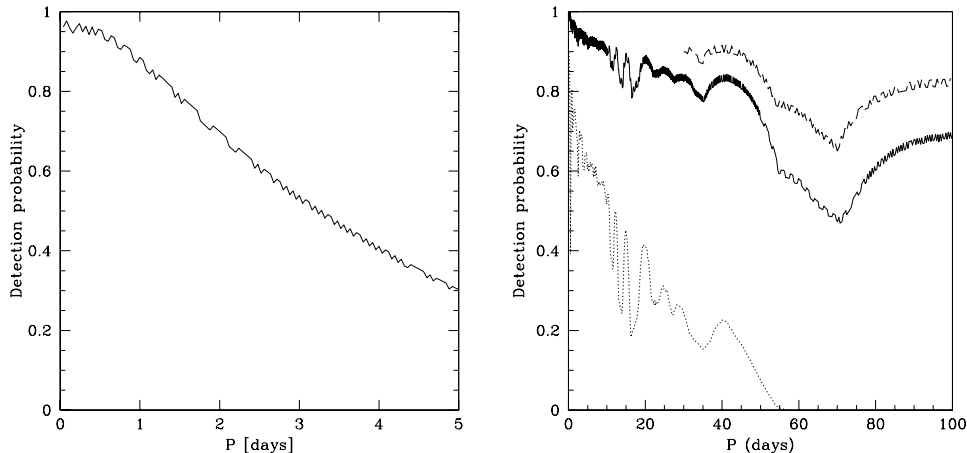


Figure 1. Binary detection probability as a function of period, calculated as in Moni Bidin et al. (2006c). *Left panel:* Probability for the NGC 6752 survey, assuming a $0.5 M_{\odot}$ mass companion. *Right panel:* Probability for the NGC 2808 survey. The solid and dotted lines are calculated under the assumptions of a $0.5 M_{\odot}$ and a $0.1 M_{\odot}$ companion, respectively, and a 3σ threshold of 10 km s^{-1} . The dashed line refers to the case of a wide, $0.5 M_{\odot}$ companion, and a 3σ threshold of 6 km s^{-1} .

cluster is; in addition, it must still be clarified whether a low f is a common feature among GCs. Finally, the role of wide binaries and/or low-mass companions has yet to be investigated in detail.

3. New Results on NGC 6752

Recently, in one observing night at VLT-UT2, we collected four high-resolution spectra ($R = 18,000$) for 54 EHB stars in NGC 6752, using the FLAMES-GIRAFFE spectrograph (setup H7A). Because of the fact that the observations were limited to only one night, the survey is sensitive only to the shortest periods (see Fig. 1). For this reason, we restrict our analysis to $P \leq 5 \text{ d}$, for which we have a detection probability higher than 40%. We consider this to be a minor problem, since the bulk of known close-binary sdB systems peaks around $P = 1 \text{ d}$ in the field, systems with $P \geq 5 \text{ d}$ merely constituting the tail end of the period distribution (see, for example, Morales-Rueda et al. 2003).

Radial velocities were measured by cross-correlating (Tonry & Davis 1979) the H_{β} line with full wings. The adopted synthetic template was chosen from the library of Munari et al. (2005). We explicitly avoided weaker metallic lines, because their quite unpredictable shape in our high-resolution, low-S/N spectra resulted in distorting the cross-correlation function without adding any information about the position of its peak. The errors in the RV variations were calculated as the quadratic sum of errors in the single RV measurements, but by accurate analysis of cooler stars included in the sample we found that this procedure underestimated the error by a factor of 1.44. We applied such a correction factor to obtain the final errors. Thirteen targets were excluded for different

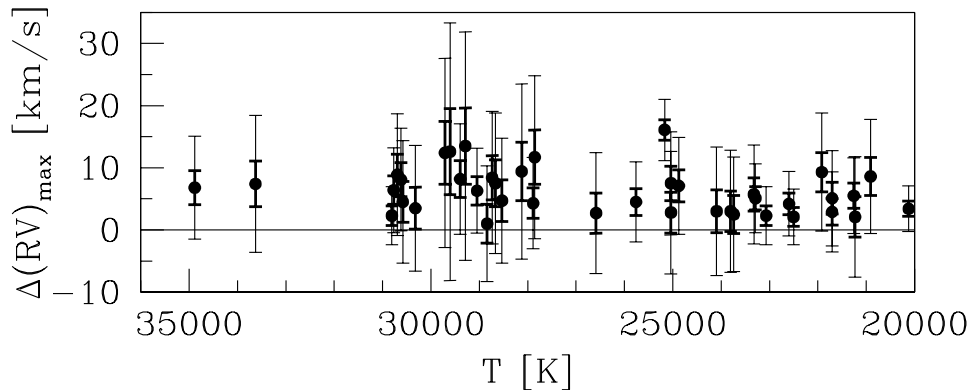


Figure 2. Results for NGC 6752. The absolute value of the maximum RV variation for each star is plotted against the effective temperature, evaluated on the basis of the color-temperature relation from Moni Bidin et al. (2006c). The thick error bar is the 1σ value, while the thinner one is the 3σ threshold.

reasons (light contamination from nearby lamp fibers, one or more spectra with too low S/N, star badly centered in the fiber).

Our results are shown in Fig. 2, where we plot the maximum RV variation as a function of the effective temperature. The 3σ threshold is on average 10 km s^{-1} . We detect only one target (at $T_{\text{eff}} \approx 25,000 \text{ K}$) showing a variation greater than this threshold ($16.1 \pm 1.6 \text{ km s}^{-1}$). This star is the same one (#5865) for which Moni Bidin et al. (2007) find evidence for a cool MS companion. Hence, it clearly is a sdB+MS close system, the first one ever discovered in a GC.

With the detection probability plotted in Fig. 1 and assuming the detection of one binary system out of 41 targets, we performed a statistical calculation as in Moni Bidin et al. (2006c). We assumed both a flat period distribution and a Gaussian one in $\log P$, but the resulting differences are negligible. The best estimate (most probable value) of the close binary fraction is $f_{P \leq 5 \text{ d}} = 4\%$. We also find that, at the 95% confidence level, $f_{P \leq 5 \text{ d}} \leq 16\%$, in good agreement with previous results for this cluster.

4. NGC 2808: Preliminary Results

We are performing an extensive search for binaries among EHB stars in the globular cluster NGC 2808, using the same instrument and methods as in the investigation presented in the previous section.

In NGC 2808 we observed 27 targets twice in each of the six observing half-nights distributed in the course of 71 days. The survey is optimized to search for binaries of any expected type. The 3σ threshold is about 10 km s^{-1} , and given the good temporal distribution of observations the resulting detection probability is very high ($\geq 80\%$) for periods $P \leq 40$ days (see Fig. 1). For wider binaries the sensitivity drops slowly, but they are not expected to show noticeable variations within a 4h interval, hence we can sum the two spectra collected each night and reach a $3\sigma = 6 \text{ km s}^{-1}$ threshold. The probability of

detecting binaries with low-mass companions is also high for the shortest periods ($P \leq 10$ days) observed among field sdBs.

Here we present some preliminary results of this ongoing project. The analysis is still in a first stage, so the present discussion merely provide a hint into what the final results may turn out to be. We analyzed the data collected in the first 4 nights for 6 EHB targets, spanning a temporal interval of 6 days. Hence we are still dealing with close binaries only. We find two stars showing variations greater than 3σ . One of them (around 21,000 K) needs further accurate study because variations are neither high nor far from the 3σ threshold. The hotter one at about 24,000 K, on the other hand, shows large variations that can hardly be explained as the result of inaccuracies in our analysis. A seventh star currently under study seems to present a similar behavior.

This preliminary overview of our data suggests that, at variance with other clusters studied so far, close binaries could be relatively common among the NGC 2808 EHB star population. It is worth considering that the sampled analyzed so far is small, and the statistic is still too poor.

5. Discussion

With our new investigation we confirm that close binaries are indeed very rare among EHB stars in NGC 6752. Our estimated upper limit for the close binary fraction agrees well with previous results, and the most probable value is small (4%). The difference between field sdB stars and their analogs in this cluster is evident. Still nothing can be said about other types of binaries found among field sdBs, i.e. wide binaries and short-period sdBs with very low-mass companions. We are working to fill this gap, but investigations of more clusters are also needed.

There are indications that close EHB systems are rare also in two other GCs investigated so far, namely M 80 and NGC 5986. This points to a difference between the formation of sdB stars inside and outside GCs, and any successful model must explain this observational constraint.

Close binary sdB stars are considered the progeny of systems that underwent one or two common envelope (CE) phases (Han et al. 2002). Accordingly, this mechanism should not be efficient inside GCs, contrary to what is observed in the field. Our present knowledge still cannot clarify the role of other binary channels that are theoretically expected to produce sdBs, such as the stable Roche Lobe Overflow (RLOF) channel (which produces wide-orbit binaries) and the merger channel (whose progeny are single sdB stars).

Moni Bidin et al. (2007, submitted) propose that among different sdB populations an f -age relation should exist, because the CE channel should be less efficient with increasing age. Detailed searches for long-period EHB binaries could test their hypothesis, but wide binaries could also be lacking, if either the merger channel or single-star evolution are the main sdB formation mechanisms inside GCs. In fact, the merger channel should be more efficient for old populations (Han et al. 2007, their Fig. 7), and it could also be enhanced by stellar interactions (Bailyn & Iben 1989). Wide binaries, on the other hand, can be easily disrupted in dense environments (Heggie 1975). In any case, Moni Bidin et al. (2006c) point out that the lack of a radial gradient for EHB stars in GCs (as

discussed in §1) puts their binary origin in doubt, because typical systems as observed in the field should exceed the turnoff mass (about $0.7 - 0.8 M_{\odot}$), and thus migrate toward the central regions due to mass segregation effects. Moreover, we would expect that members of disrupted systems or sdBs formed through stellar encounters and collisions would be a kinematically hotter population, but in our data we find no evidence of a difference with respect to other HB stars.

It is well known that even MS and RGB binaries are much more frequent in the field than in GCs (see for example Sollima et al. 2007, for a recent study), but this would not suffice to account for the difference in EHB binary fraction, as it would imply that sdB formation and binarity are unrelated – at variance with our present understanding of these stars. Moreover, the binary fraction among MS field stars could even be noticeably lower than has been assumed so far (Lada 2006).

NGC 2808 could be a remarkably different case. If our preliminary results are confirmed, this cluster would be relatively rich in close EHB binaries, in contrast to the other clusters studied so far. It is tantalizing to relate this discrepancy to other well-known peculiarities of the cluster, as its multimodal HB (Sosin et al. 1997) or its triple MS (Piotto et al. 2007), but our study is still in too early a stage and the sample analyzed is too small to allow definitive conclusions.

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